A FEEDBACK SYSTEM FOR AUTOMATIC CONTROL
OF SIMULATED AERODYNAMIC HEATING

A THESIS

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By

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The author acknowledges the valuable assistance and advice of Professor W. H. Horton during the preparation of this thesis.

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TABLE OF SYMBOLS

q heat flow $(t_{aw} - t_s)h$

q_d heat flow desired

q_m measured heat flow

q_r radiant heat flow

h heat transfer coefficient

t_{aw} adiabatic wall temperature

t_s surface temperature

c control voltage

LIST OF FIGURES

SUMMARY

The Stanford University radiant heating structural test facility is described in Appendix B. This paper deals with the design and construction of components and the techniques used to close a feedback loop for automatic control of the facility. It shows how the output from a time-shared computer system solving the Newtonian convective heat transfer equation can be combined with a measured heat flow and used to control an infra-red radiation test facility to simulate the heat environment corresponding to a prescribed flight profile.

INTRODUCTION

A recent flight report of the X-15 research craft significantly illustrates the problem of aerodynamic heating.

> "The X-15 rocket plane, in a scorching low-level dash, underwent today its longest sustained test.
>
> Engineers estimated that the X-15 flew for more than a minute with the little rocket research craft's skin at a temperature between 900 and 1000 degrees.
>
> In previous flights it has been subjected to such heat only for a few seconds.
>
> The X-15's designed heat limit for fuselage and major surfaces is 1200 degrees. Some points, like the leading edges of the wings, can take more. Maximum recorded so far on such edges is more than 1400 degrees."[1*]

Heating effects, such as those encountered by the X-15, introduce a multitude of problems for the structural design engineers. These effects cause reduced structural strength and possibly critical reductions in structural stiffness. In addition, thermal stresses are introduced by the temperature gradients. The elimination of such problems by mechanical air conditioning is not practical, since at Mach 3.5 the power required for cooling becomes nearly equal to the power required for propulsion.[2] Supersonic aircraft structures must therefore be designed to withstand the effects of these high temperatures. The solution of such design problems by analytic means is a best extremely difficult, although significant strides toward such solutions are being made with the employment of high speed digital computers. The accepted method of solution today is to test the actual structure under conditions which closely simulate those which will be encountered in flight.

The simulation of aerodynamic heating for design test purposes has been an important area of research over the past decade. Possible methods of simulating heat transfer to a test surface include thermal blankets, heated fluids or gasses,[3] inductive heating,[4] and radiation from infra-red sources. It is generally agreed that the best of these methods for simulated heating up to about Mach 6 is infra-red radiation.[5]

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[*] Superscript numerals refer to references at the end of the report.

It is possible with infra-red heaters to obtain intensities of 150 Kilowatts per ft.[2] Thus, simulation of heating for most supersonic manned vehicles is feasible.

The infra-red radiation system also has advantages over other methods in that with such a system the test specimen is visible and accessible. The ready accessibility makes it easier to attach loading points for the simulation of aerodynamic loading simultaneously with heating.[6]

A test facility based on infra-red heating has been constructed at Stanford University and is described in detail in Appendix B. This facility at present simulates only aerodynamic heating but will be expanded in the future to include simulation of aerodynamic loading. The facility is essentially automatic in that aerodynamic data for a specific flight profile is fed into a computer which derives a command signal for heat flow desired.

This thesis deals primarily with the loop closing technique and the actual control of the infra-red heaters. A device which measures the radiant heat intensity is used to close the control loop for automatic control of the system as it follows the computed heat profile. Design and calibration of this device is covered in detail in Appendix A.

I. DERIVATION OF CONTROL TERM

The time-shared computing system is described in Reference 7. This system generates a pulse voltage output proportional to the heat flow required for each channel of control. Each pulse is sent to a peak follower circuit which uses an operational amplifier to produce a constant voltage output equal to the peak value of the pulse input. (See Fig. 1) The continuous output voltage for heat flow desired (q_d) is then available for comparison with the signal proportional to the measured heat flow (q_m). q_m is either a millivolt signal from the radiation transducer or a signal from the automatic heat flow computing element described in Reference 8. The signal from the heat flow measuring system is amplified to a level equal to one-half that of a corresponding q_d by a chopper stabilized operational amplifier. The signal q_m is then subtracted from q_d in a standard analogue summing circuit. The output is a control voltage (C) used to regulate the power supplied by the saturable core reactors. Due to the two-to-one scaling of q_d and q_m the control voltage consists of the sum of a set-point voltage and an error voltage.

Since the most expensive parts of the comparator arrangement are the chopper stabilized amplifiers, which cost $85 each, the possibility of time-sharing one of these amplifiers to provide the feedback signal for all four channels has been considered. Presently investigation is being conducted into the feasibility of using a rotary switch for high speed switching of millivolt level signals.[8] When this investigation is complete, the system will be modified accordingly. A diagram of the basic system modified in such a manner is shown in Figure 2.

The computer system supplies a new value of q_d to each channel every 1.2 seconds. By adding a good high speed switch the radiation signal for each channel could be switched to the amplifier and comparator 10 times or more during the 1.2 second period. This would result in an error signal which would be corrected 10 or more times before a new command signal is generated. Though this has not yet been attempted, research indicates that such an error signal would be sufficiently accurate for good control.

II. POWER REGULATORS AND THEIR CONTROL

The power regulators for the heaters are General Electric saturable core reactors. Reference 9 discusses in detail the relative merits of several devices suitable for such application. Although saturable core reactors are not the best units for the type of power regulation required, their use in this installation was dictated by availability. The reactors are essentially dc polarized chokes inserted in the circuit of a transformer. When pre-magnetization is increased by passing current through the dc winding, the ac resistance of the choke reduces and the power output increases.[9] Each unit consists of three reactors and a control system which supplies the required dc current for the chokes. The units act as regulators for three phase ac power. The control systems were designed primarily for control of temperature in large electric furnaces and required minor modifications to meet the needs of this installation. Two thyratron rectifier tubes provide the dc power for each unit. The output of the thyratrons is regulated by an electronic circuit.[10] The controlling factor of this circuit is the grid voltage of one vacuum tube. Provisions are incorporated for both manual and automatic variation of the grid voltage. The manual control has been retained in its present form for regulation of the reactor power output. For automatic control, the grid voltage is normally supplied by the secondary of a transformer, whose primary is connected in a bridge circuit consisting of band-width, position coarse, and position fine potentiometers, as well as the slide-wire in a temperature control instrument. This method is satisfactory for furnace control but does not have rapid enough response time for control of the infra-red system. For our application the control transformer has been disconnected. In its place a constant dc voltage is supplied from a battery. This is adjusted by a potential divider to the exact value required to keep the control tube cut off. The value of the cut-off voltage varies from unit to unit but is usually about 10 volts. A reduction in grid voltage turns the unit on and full power is reached at about 5 volts. The control voltage from the comparator is also supplied to the grid but is in opposition to the cut-off voltage. (See Fig. 3) As the control voltage is increased, the net voltage on the grid decreases turning the tube on and increasing the power output to

the heaters. The system then operates so that the error voltage is reduced and the operation point converges to that required by the set-point portion of the control signal. For example, if cut-off is 10 volts and full-on 5 volts, the q_d signal for maximum heat would be set to 10 volts (twice the operating range) and the signal for maximum q_m would be set to one half this value. If full power is then commanded, the q_d signal opposes the cut-off voltage resulting in zero grid volts and full power from the reactors. As the feedback signal increases, the control voltage rises to 5 volts and the reactors remain in operation at full power. If one half maximum heating is demanded, q_d would be 5 volts and the reactors would again produce full power. In this case, however, as the feedback signal, hence the control voltage increases, the power output is reduced until the point is reached where the reactors are operating at half power. Any change from this condition results in an error signal which changes the control voltage. This changes the power output to maintain the radiant intensity at the desired value. Figure 4 is a diagram of the complete control loop for one operating channel.

No formal analysis of the control system was attempted but rather it was tried and found to work reasonably well. Since the operating speed of the computer elements is rather slow, there is ample time for the system to respond and no problems of stability have been encountered.

III. MAIN POWER SYSTEM AND LOAD CONNECTIONS

Power is supplied to the saturable core reactors from two 300 KVA, 480 volt, 3 phase transformers. Each reactor unit is rated at 75 KVA, 480 volts, 3 phase. The duty cycle under which this equipment is normally operated is such that the system can be overloaded to more than twice rated value. Under these conditions over 1 megawatt of power is available.

The basic heating element is a General Electric tubular quartz heater. It consists of a tungsten filament supported in a sealed quartz tube of 3/8 inch diameter and 12 inch length. Each unit is rated at 100 watts at 220 volts. Heaters of the same external size are available with a larger filament to give an output of 2000 watts at 220 volts. With some modifications to the arrays, the use of the 2000 watt heaters is possible when higher rates of heat flow are desired. Each heater array consists of six heaters mounted side by side in a fixture constructed of transite and aluminum. (See Appendix B) Arrays are connected in delta to the power output lines from the saturable core reactor units. One unit simultaneously controls the arrays for heating a specific area of the test specimen. Since the maximum line to line voltage is 480, the heaters may be operated at slightly more than double their rated voltage. Under these conditions power produced is approximately 3.0 kilowatts per heater. Each array covers about one third of a square foot so the maximum radiant power is 60 KW per square foot. This figure may be significantly raised by the rearrangement of the heater elements.

IV. MULTI-CHANNEL HEATING

Individual channels of control operate as previously described to heat specific areas of a test specimen. The fact that such operation is satisfactory in all respects is indicated in the results of Section V. The operation of several channels of heating simultaneously does, however, introduce some additional complications into the control problem.

The heaters for one area of the test structure cause a small feedback signal from the transducer for the adjoining area. A factor of electrical cross-coupling is thus introduced into the control system. Efficient shielding of the transducers and judicious placement of the heater arrays have to a large extent eliminated the problem. In a program which requires wide variation of heat from one channel and a relatively constant low value of heat from the adjacent channel care must be taken to avoid any cross-coupling. Some instances of such operation have been discovered. In these cases the large fluctuations in the high power channel did cause some minor fluctuations in the adjacent channel operating at low power. The oscillations damped out however and no problems of system stability arose.

Additional cross-coupling effects are introduced by the test structure itself as it is heated at different rates over separate areas. These effects necessarily involve the characteristics of the test structure and thus become very complicated. The limitation of time available for this project prevented any investigation in this direction.

V. COMPONENT OPERATION AND RESULTS

The significant results of the project may best be demonstrated by tests performed on the system component. To demonstrate the control of the saturable core reactors several tests were performed with an arbitrary voltage as the command signal, C . The command signal was recorded simultaneously with a signal proportional to the power output of the reactors. Figures 5 and 6 are recordings of these tests. The control voltage, in opposition to the constant d-c cut-off voltage, was increased in a series of steps. The output of the reactors is shown in the figures as the envelope of the a-c power output. Comparison of figures 5 and 6 reveals that a specific value of command voltage always results in the same output from the reactors. This demonstrates the repeatability which is an essential feature of any control system. Figure 7 is a record of a step input of control voltage and the corresponding reactor output. This figure is on an expanded time scale to show the response time of the reactors which can be seen to be approximately one second. This is adequate response time for compatability with the other components of the system.

To demonstrate the operation of the comparator an arbitrary value for q_d was introduced to the comparator. A voltage corresponding to a_m was then subtracted from q_d in the comparator to give the control voltage. Figures 8 and 9 are records of these voltages and their differences. These tests showed satisfactory and repeatable operation of the comparator and gave rise to no problems of stability.

VI. CONCLUSIONS

The following conclusions are drawn from the knowledge gained by the author during the design and construction of this test facility.

(1) The use of standard analogue computer elements appears to be a satisfactory means for the computation and control required in such a test facility.

(2) Time sharing of elements results in a considerable saving in cost with only small reductions in performance. The possibility of more time sharing is worthy of further investigation and experimentation.

(3) Saturable core reactors are completely adequate as voltage varying devices, unless extremely high responses are required. Such a system would also require more sophisticated computational methods.

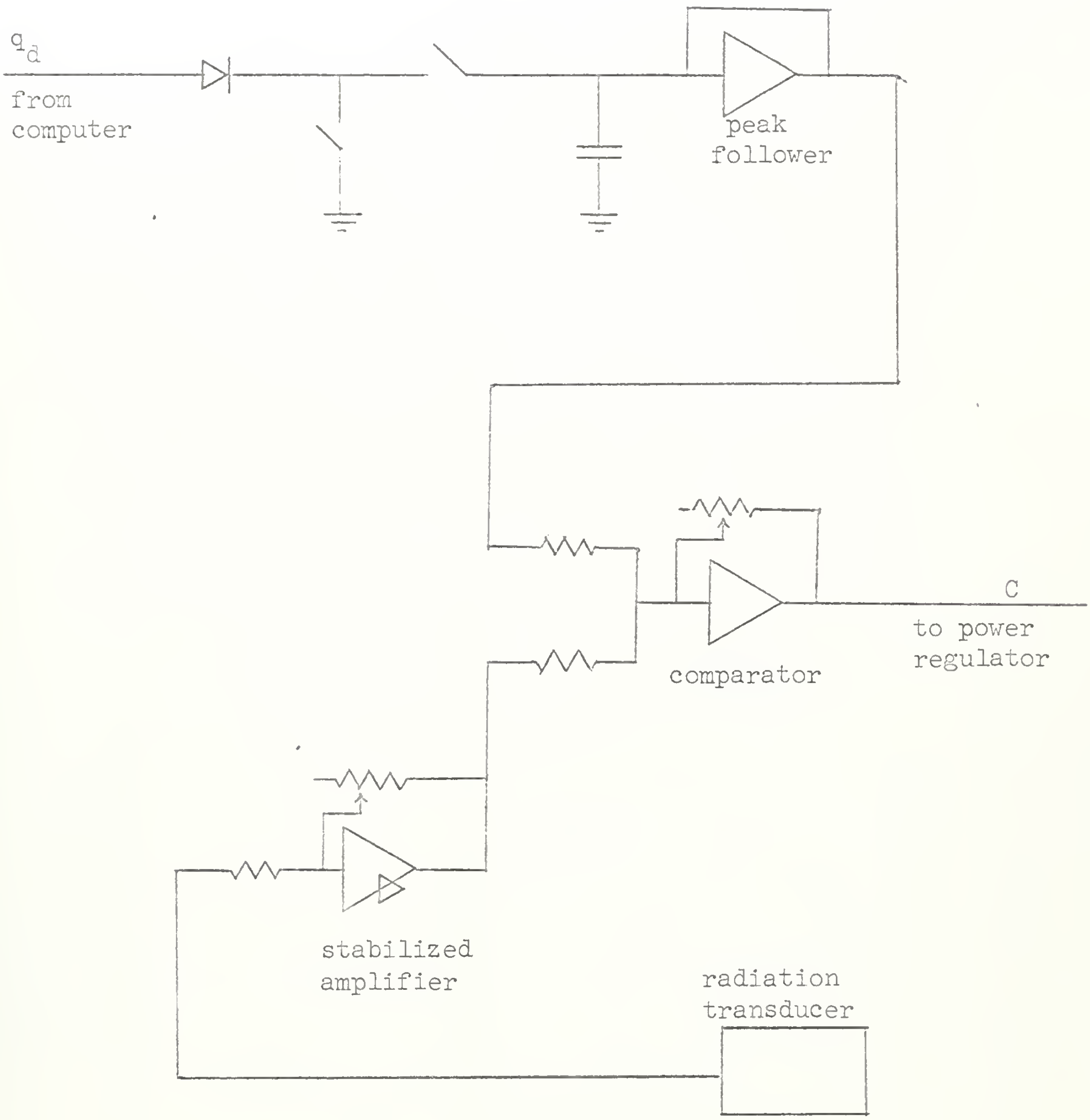

Fig. 1. Comparator Arrangement for One Channel. All Channels are Identical.

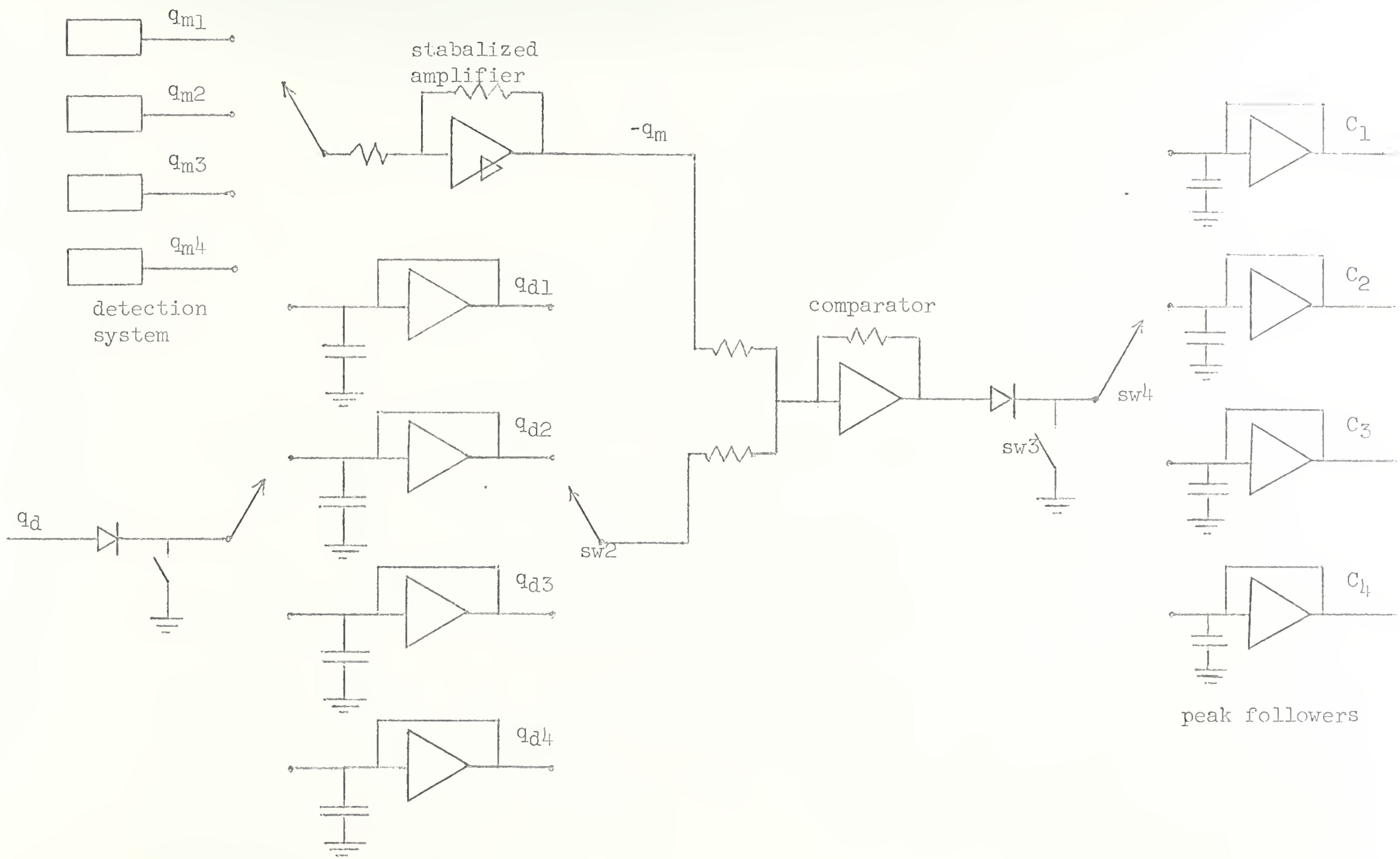

Fig. 2. Time Sharing the Transducer Amplifier and the Comparator. Switches 1, 2, 3, and 4 are Mechanically Linked and Run at High Speed.

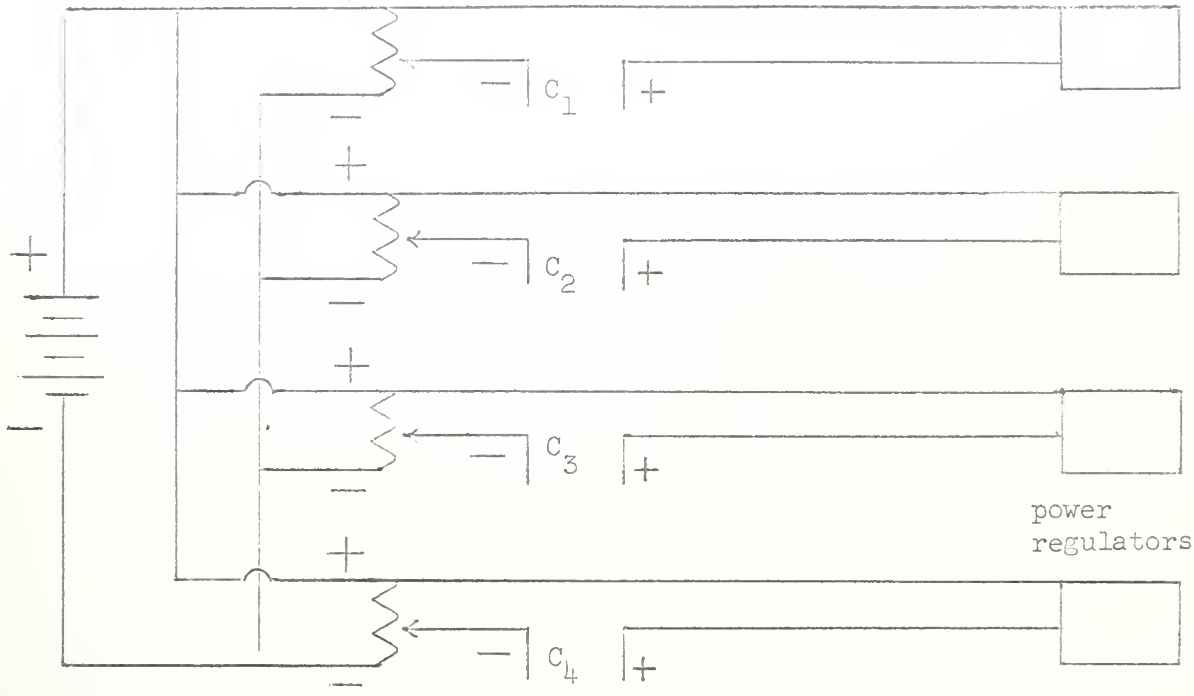

Fig. 3. Control of Power Regulators.

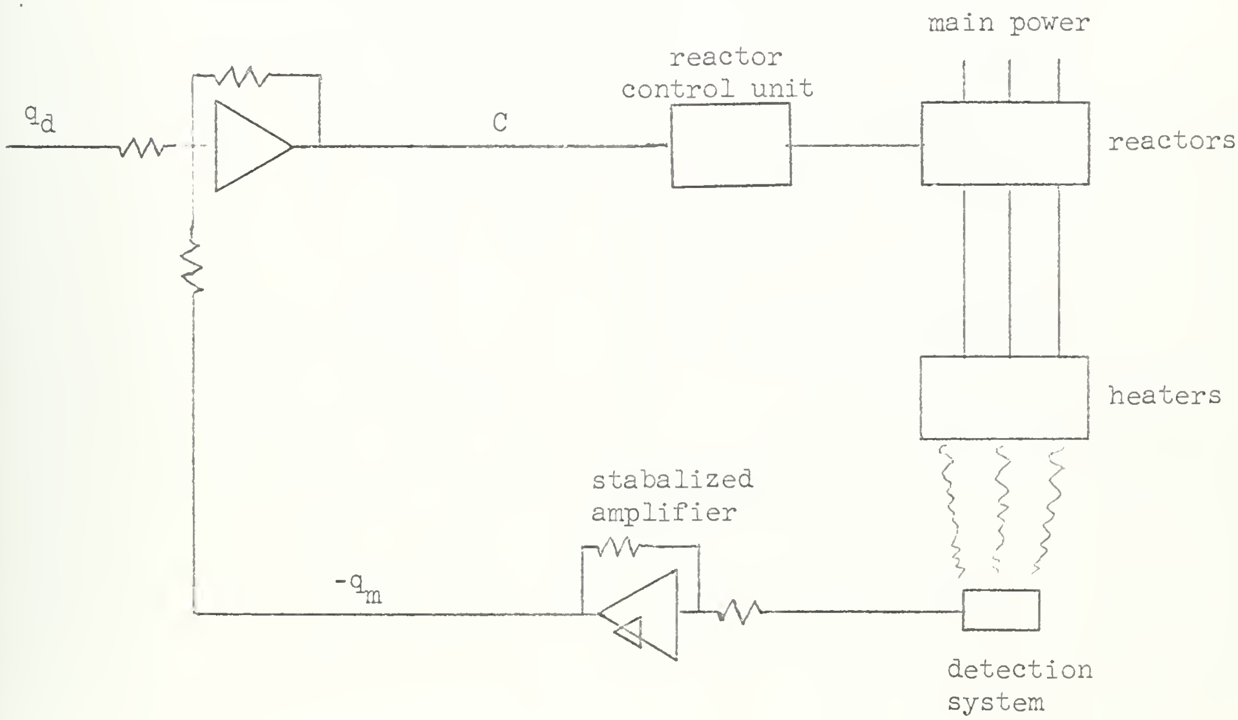

Fig. 4. Complete Control Loop for One Channel.

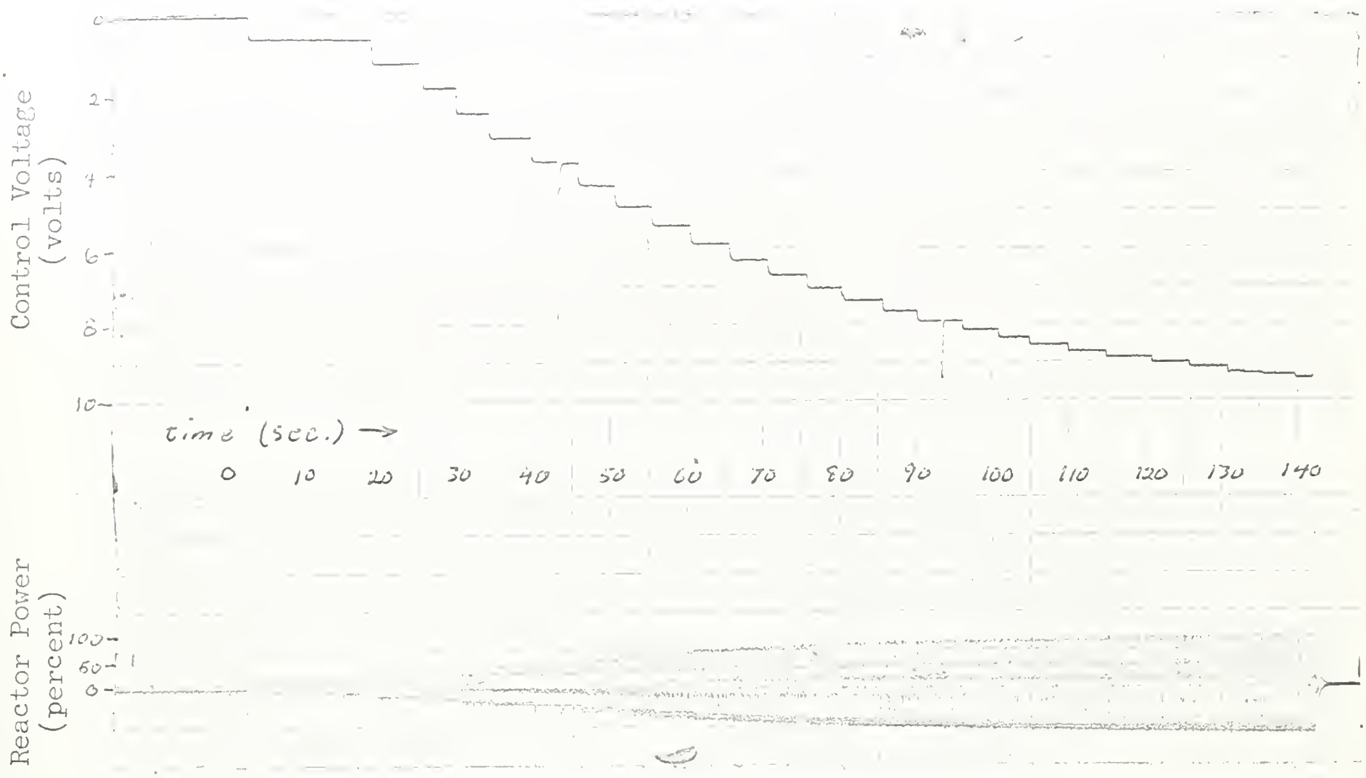

Fig. 5. Control Voltage and Power Output.

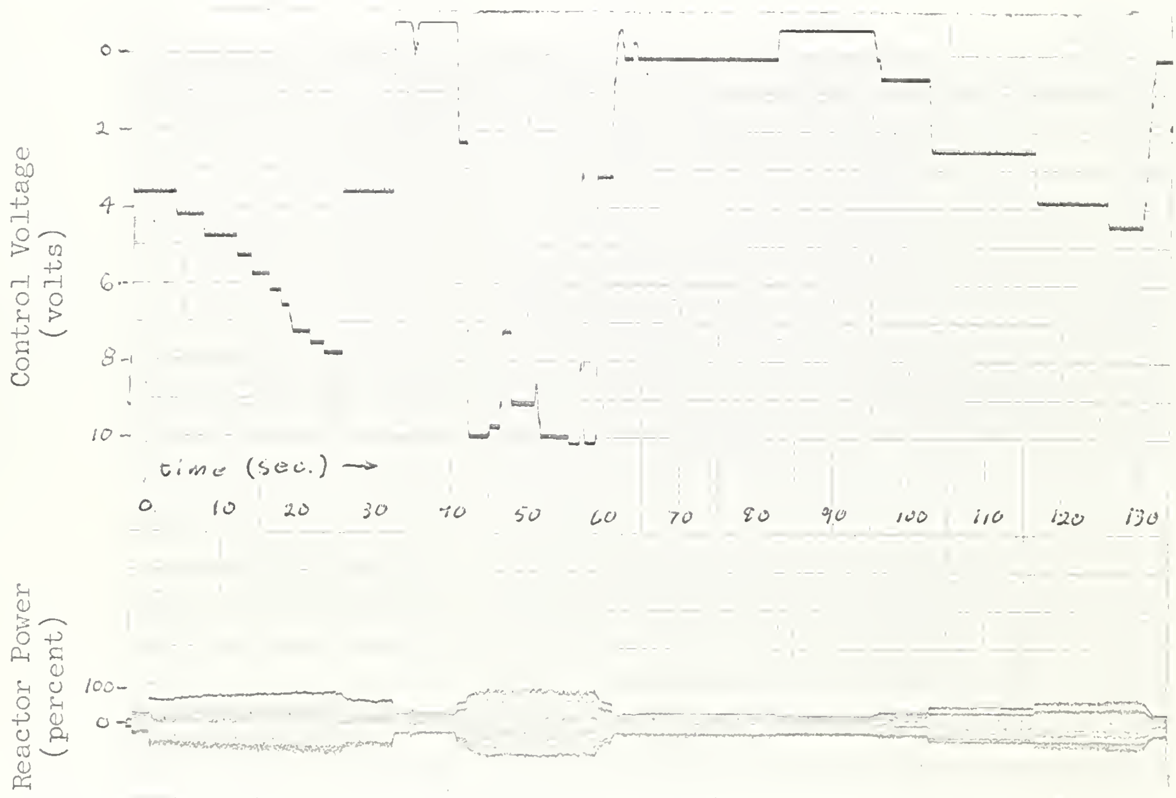

Fig. 6. Control Voltage and Power Output.

Fig. 7. Reactor Response Time.

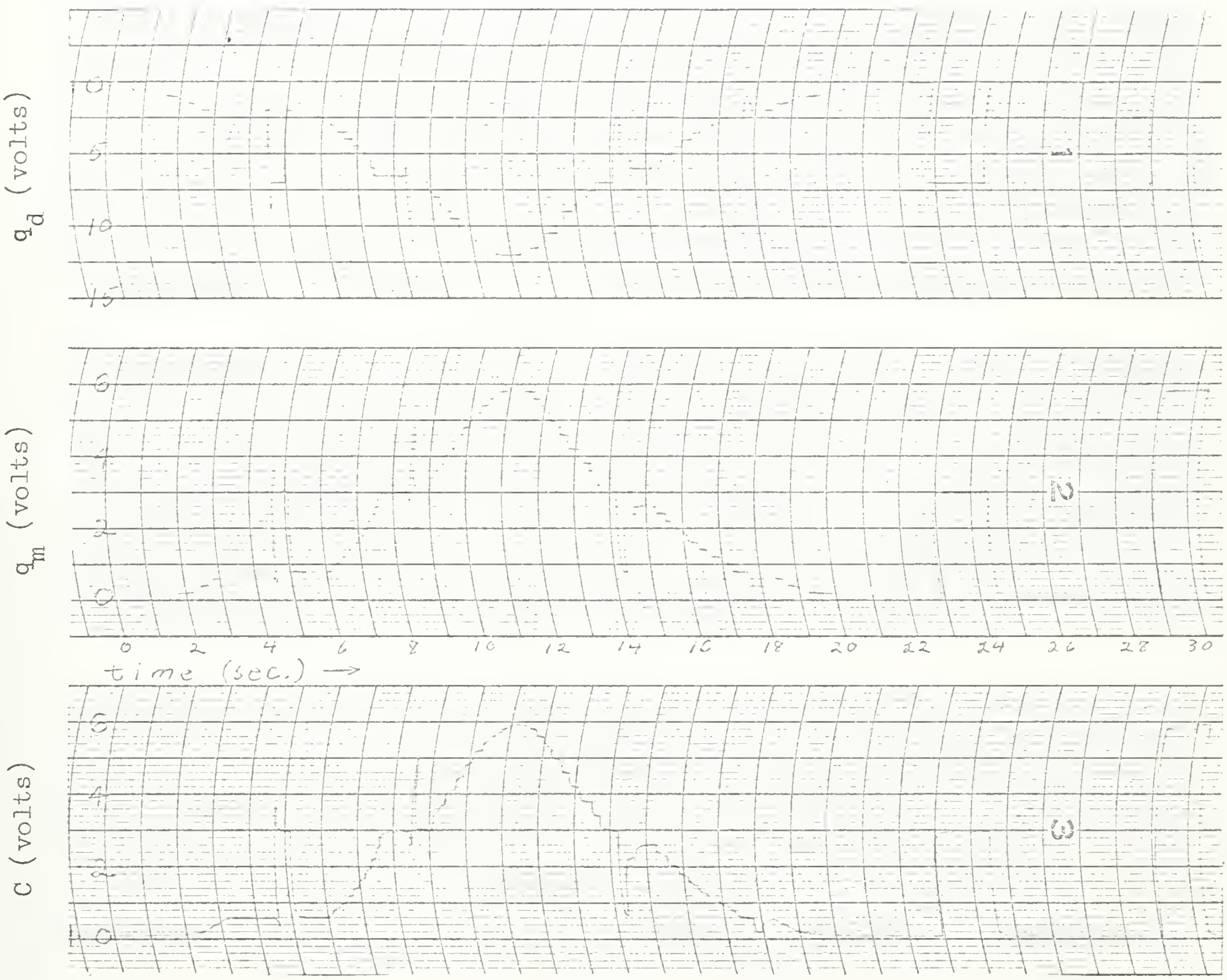

Fig. 8. Comparator Operation

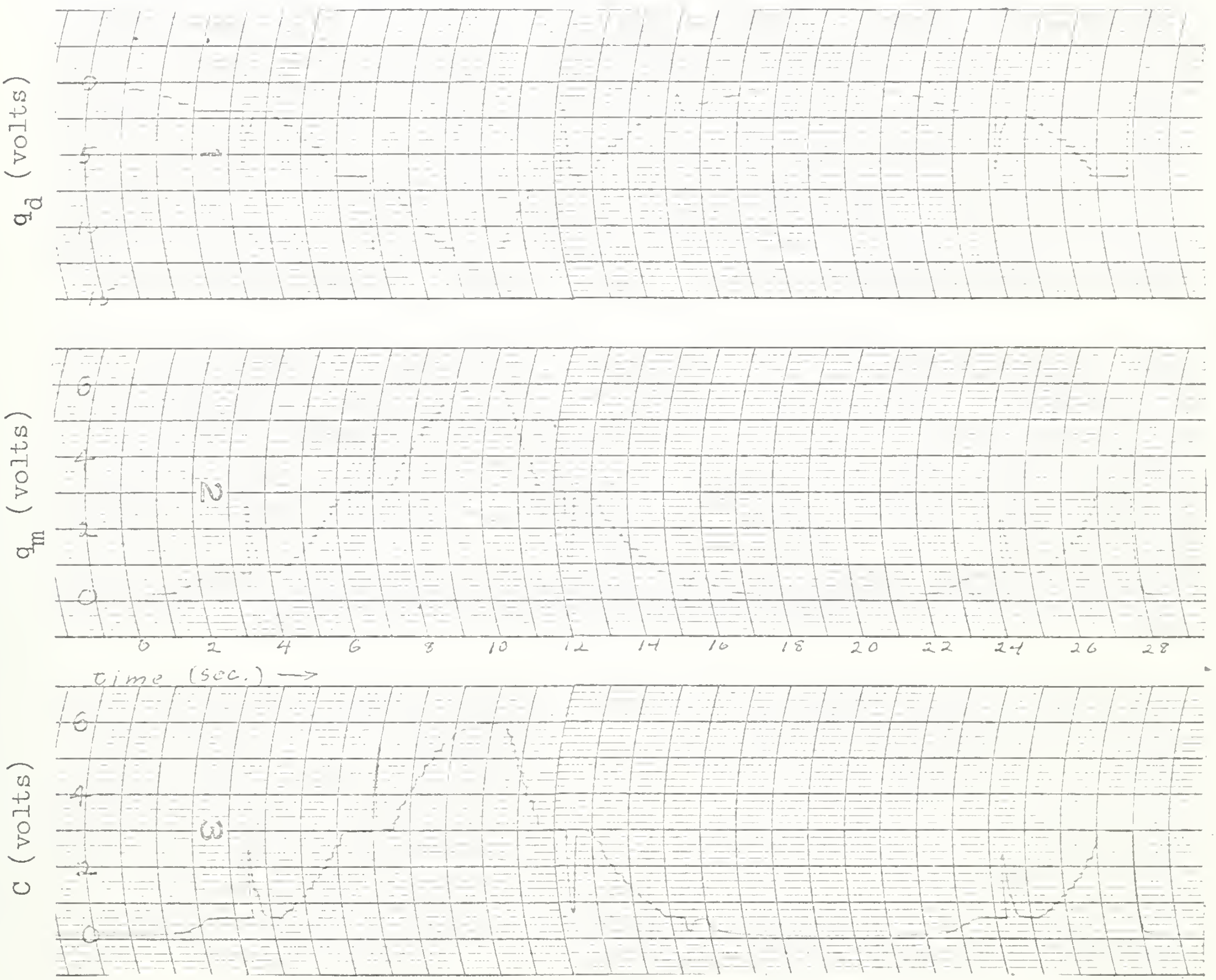

Fig. 9. Comparator Operation.

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APPENDIX A: A TRANSDUCER FOR THE MEASUREMENT OF RADIANT HEAT

The basis of most radiation sensing systems is the establishment of a temperature difference proportional to the radiation to be measured. Generally the temperature difference is established between an element of very low thermal inertia and a substantial sink. A transducer for measuring infra-red intensity is described in detail in Reference 9. Instruments of this type have been produced commercially. They use a copper tube with cooling water flowing through it for the thermal sink. A very thin constantan disc is attached to a transverse passage through the tube. The heat flow in the disc is radial and the temperature in the center can be shown to be proportional to the radiant intensity. Wires attached to the tube and to the disc center constitute a difference thermocouple the output of which is proportional to the radiant intensity. Several of these instruments may be connected in series in order to average out errors of individual thermocouples and to provide greater sensitivity. The instruments were used in this system in the same manner described in Reference 9. One instrument faces the radiant source and another the test specimen. These are connected in opposition so that the output is proportional to the difference between incident and reflected radiation. The instruments have excellent time response which, with a thin enough disc, can be as low as one thousandth of a second.

For calibration of the transducers a calorimeter was made from stainless steel. It consisted of a 1/32 inch thick disc, 3/4 inch in diameter. A diagram of the calibration rig is given in Figure A1 and the calorimeter is pictured in Figure A2. The calorimeter was guarded along its edges by a ring of the same material and on its rear face by another disc. In this way the heat losses from the calorimeter were made negligibly small. This was verified by recording output from thermocouples attached to various points on the rear face of the calorimeter. The temperature of the disc was found to rise uniformly when subjected to a radiant field. A series of temperature vs. time records was then made for the calorimeter in the uniform field. The records, together with the known area and properties of the calorimeter, enabled calculation of heat absorption rate. The tests were performed with the calorimeter at the same distance from the radiant source that a test structure would

normally be located. A radiation transducer was mounted in position of the heater array used for the test. The output of the transducer was recorded simultaneously with the calorimeter temperature. The result of each test was thus a transducer output which corresponded to the calculated heat absorption rate. During actual structural test the same transducer signal will represent the same heat absorption rate by the test structure. One transducer was calibrated in this manner and the other then calibrated against the one. The heating rate computer system was also calibrated by the use of this calorimeter test arrangement.

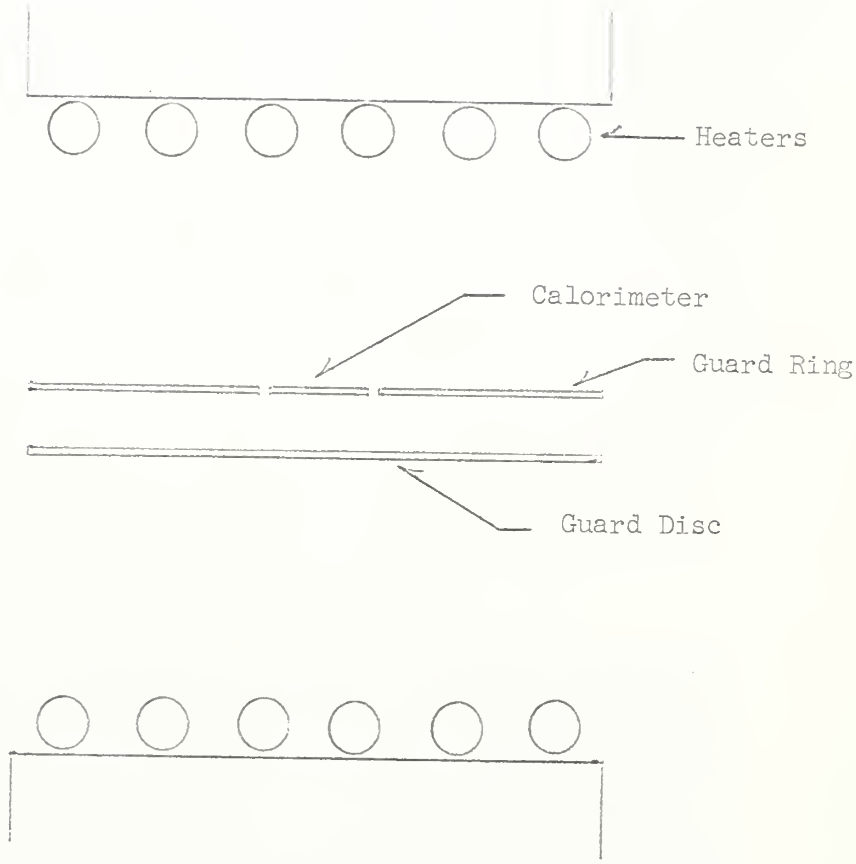
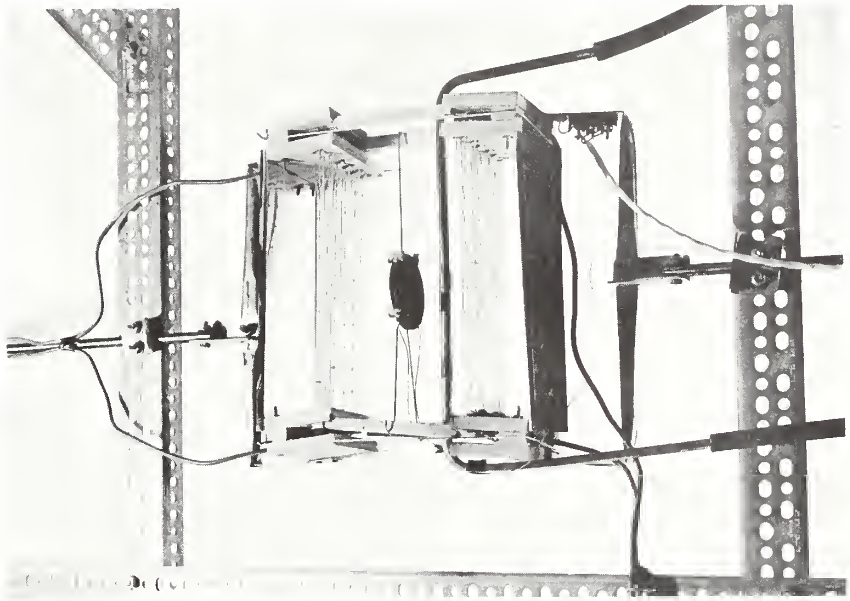


Fig. A-1. Calorimeter Test Rig.



Calorimeter Test Equipment

Fig. A-2

Calorimeter

Fig. A-3

APPENDIX B

STANFORD UNIVERSITY RADIANT HEATING STRUCTURAL TEST FACILITY

by

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APPENDIX B: STANFORD UNIVERSITY RADIANT HEATING STRUCTURAL TEST FACILITY

I. INTRODUCTION

The need for aerodynamic heat simulation in structural testing of supersonic aircraft is well recognized. Thus, the authors undertook the design and construction of a four channel radiant heating test facility at Stanford University during the summer of 1962. The system was designed to meet the following requirements: a high intensity, rapid response heat source; an adequate reflector system to direct the heat; an absorptive finish on the test specimen to permit maximum utilization of available heating power; a practical technique for surface temperature determination; a system of radiation measurement; and a computer control system to correctly vary the heat input to the test specimen.

II. SYSTEM LOGIC

Figure B-1 is a block diagram of the control system for the radiant heating test facility. Voltages analogous to h and t_{aw} are generated and then utilized by the computer along with a voltage analogous to t_s for solution of the Newtonian convective heat transfer equation, $q = h(t_{aw} - t_s)$. Another voltage (q_r) representing radiation from external sources (sun, atomic blast, etc.) is generated and then added to q in a summing circuit to give the desired heat flow signal, q_d. The comparator output, c, is the difference between q_d and q_m, the measured heat flow. The control signal causes the power regulating device to vary the power supplied to the heaters. The heat flow measurement system closes the control loop, causing the correct heat input to the test structure to be maintained. The measurement of heat input to the test specimen is made by either of two systems. The operational details of these devices are explained briefly in Section III and in detail in References [1] and [2].

III. SYSTEM DETAILS

Certain requirements are essential in a practical feedback control system for the simulation of aerodynamic heating. The requirements set for this facility are to:

(1) accurately compute desired heat flows for simulation of speeds up to Mach 6.

(2) be capable of measuring the heat inputs to the test specimen.

(3) be dependable.

(4) be safe to operate.

(5) be inexpensive as possible.

(6) be simple to operate and program.

The operations of the function generator and computer shown in Fig. B-1 are combined in the digital to analogue computer control system. This unit consists of a punched tape reader, an operational amplifier and resistance bank, two peak followers and associated capacitors, a multi-bank stepping switch, a summer, and a chopper stabilized amplifier. (Fig. B-2) The details of the individual components are given in Reference [1] and only the modus operandi is discussed here.

Values of h and t_{aw} are obtained from the Stefan-Boltzmann law. A binary coded program of these time dependent functions is made on a punched tape. This tape is placed on a reader and used in the time shared system as follows: an analogue voltage proportional to q_r is generated from a resistance network and a reference voltage in conjunction with an operational amplifier. This signal is temporarily stored. The next command is t_{aw} which is treated in the same way. The output of the temperature transducers, t_s , is amplified by a chopper stabilized amplifier and then subtracted from the stored t_{aw} analogue in a summer. The voltage difference $(t_{aw} - t_s)$ is used as the reference voltage for the next stage of the operation. This consists of giving the command, read h , and by virtue of the fact that the reference voltage is analogous to $(t_{aw} - t_s)$ the output of the system is analogous to the product $h(t_{aw} - t_s)$. Simultaneously, q and q_r are added in a summer and this voltage, analogous to q_d , is stored in a capacitor. These steps are repeated for channels two, three, and four. The digital to analog computer evaluates a new value of q_d for each channel every 1.2 seconds. Thus, by time sharing, by digital to analog conversion, and by unique computer techniques,[1] a simple and accurate means for obtaining a q_d history is realized.

There are two systems available for closing the control loop. Both systems measure the rate of heat flow to the test specimen and therefore may be used interchangeably. One system, the classic system, consists of special transducers. These essentially consist of thermocouples in conjunction with substantial heat sinks. In a radiant field the thermocouples reach an equilibrium temperature proportional to the radiant intensity. Each transducer is two thermocouples connected so that their signals oppose. One is subjected to the radiation from the heaters and the other to the reflected radiation. The output is therefore proportional to the difference between the incident and reflected radiation. This is q_m exclusive of convective losses. The heat sinks for the transducers are cooled metallic blocks. The instruments are attached directly to the sides of the heater arrays. They are calibrated in a calorimetric manner.

The other system, one especially devised for this project, consists of eighteen thermocouples arranged to obtain temperature profiles in the test specimen. A high speed stepping switch sequentially connects the thermocouple signals to an analogue computer which solves the appropriate heat flow equation. The computer is time shared by the 4 stations. The latter system is more versatile than the former since it measures net heat flow irrespective of the nature of the source. Thus convective losses in simulation are accounted for. An additional refinement to the computer permits compensation for radiant losses which the structure would normally experience in flight. Figure B-3 is a photograph of the feedback computer system.

Voltages in the control system are scaled such that at any time the prescribed q_d level is twice the anticipated q_m level. A summing circuit subtracts q_m from q_d and the output (c) is used to control the power regulating devices. Due to the two-to-one scaling the control signal consists of a set-point voltage plus an error voltage. Thus, the heaters are controlled in such a manner that the desired and actual heat inputs are equalized. This occurs when the error voltage level converges to zero and the control signal converges to the set-point voltage.

Main power is supplied through two 300 KVA, 480 volt, 3 phase, General Electric transformers. The power regulating devices consist of 75 KVA, 480 volt, 3 phase General Electric saturable core reactors and

their associated control units. Transient operation of the power equipment on an overload duty cycle makes possible peak outputs of two to three times rated value. Heating capacity of more than one megawatt is therefore feasible. Figure B-4 is a photo of the saturable core reactor units.

The basic heating elements are General Electric T.3 infra-red lamps. (See Fig. B-5) They consist of a tungsten filament supported by tantalum disc spacers in a sealed quartz tube 3/8 of an inch in diameter and 12 inches in length. Each unit is rated at 1000 watts at 220 volts. They are capable of withstanding the 480 volt peak output of the power supply and under these conditions develop approximately 3 kilowatts.

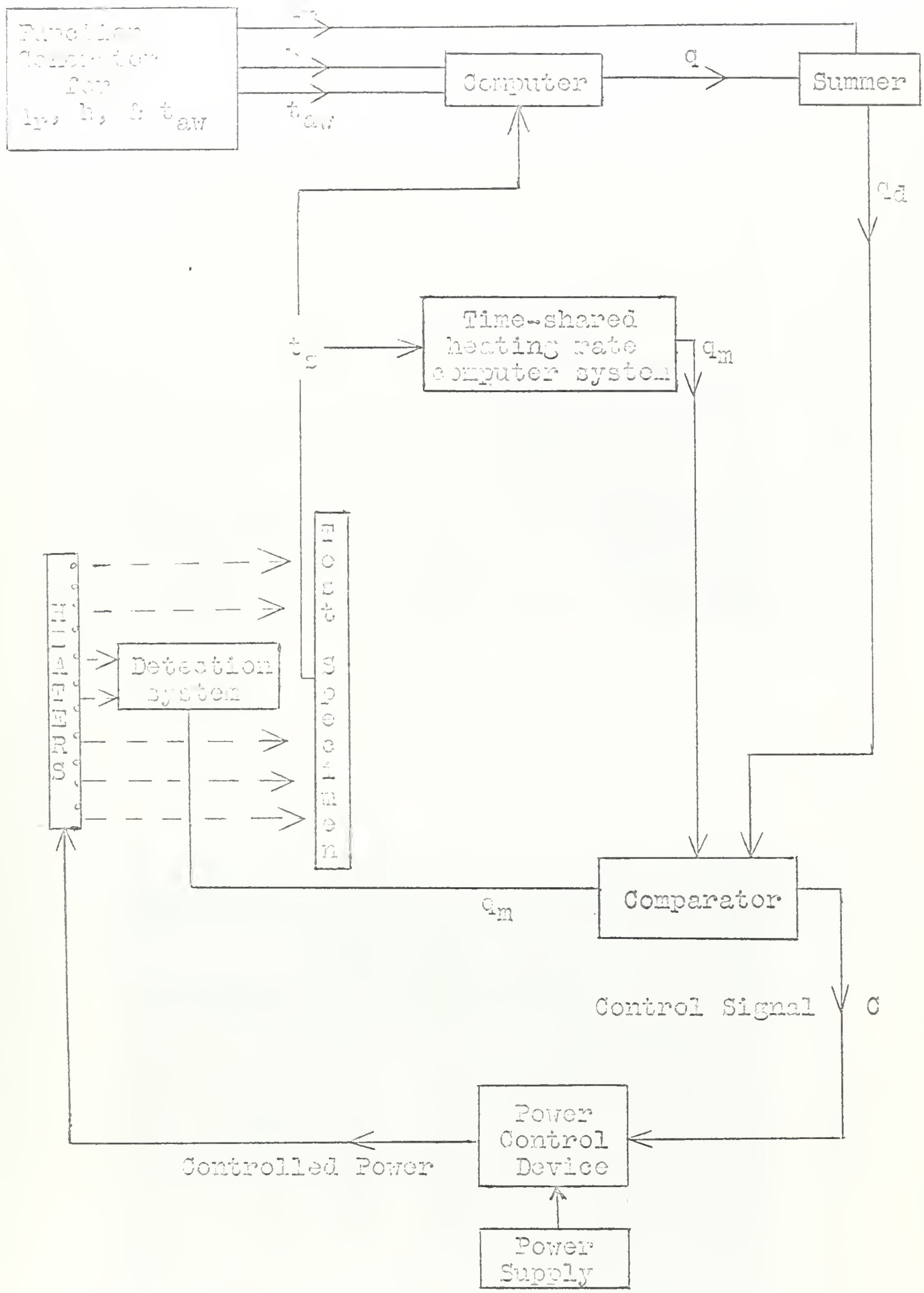
The heaters are arranged in groups of six. Figure B-6 is a photograph of one such unit. The heater arrays are connected in delta to the three phase power from the saturable core reactors. Each unit covers about one third of a square foot. Thus, the maximum radiant intensity possible with the present arrangement is about 60 kilowatts per square foot. Two thousand watt heaters of the same external size are available when higher intensities are required. Peak output of these is 6000 watts per heater. The heater arrays are quite adaptable and may be bolted to any suitable frame to surround a test structure. Special arrangements may easily be devised for special purposes, such as the heating of curved surfaces.

Figure B-7 shows an overall view of the test facility. The main items of equipment and the channels of information flow are outlined on the photograph. All control, computing and recording equipment is located in the control room. This room is on the second floor of the laboratory overlooking the test site. Large windows provide for visual observation of the structure under test. The remote location of the control room was dictated by safety considerations and provides a convenient, compact center for operation of the entire facility.

IV. CONCLUDING REMARKS

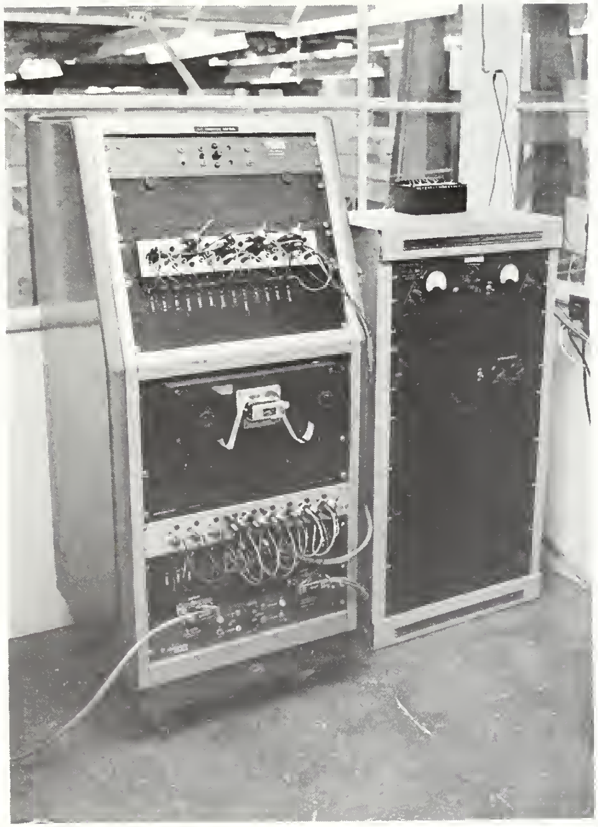
The design, construction, and operation of this test facility has proved that the concept of component time-sharing is practical in certain types of control systems. It is concluded that such time-sharing is an

economical proposition in which savings in equipment costs are balanced against slightly reduced system performance. The facility is such that it can be readily installed in any small research laboratory where cost is of prime importance.



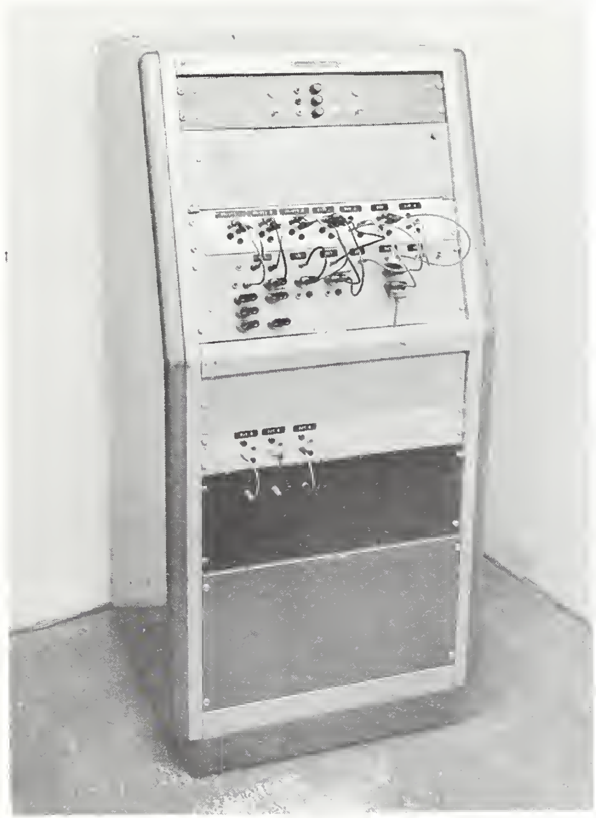
Block Diagram of a Closed Loop Control System for the Simulation of Aerodynamic Heating

Fig. B-1



Digital to Analog Computer Control

Fig. B-2



Feedback Computer

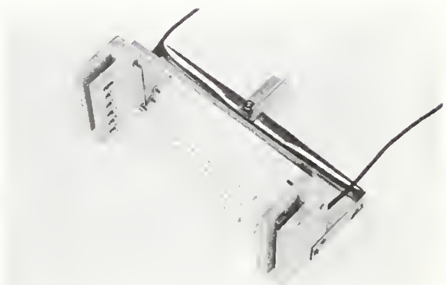
Fig. B-3

Saturable Core Reactors

Fig. B-4

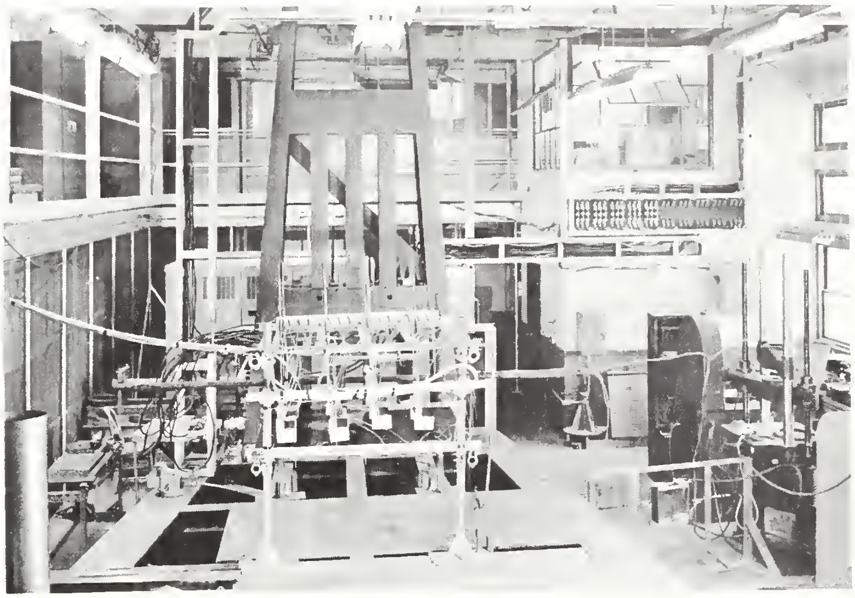
Infra-Red Heater

Fig. B-5



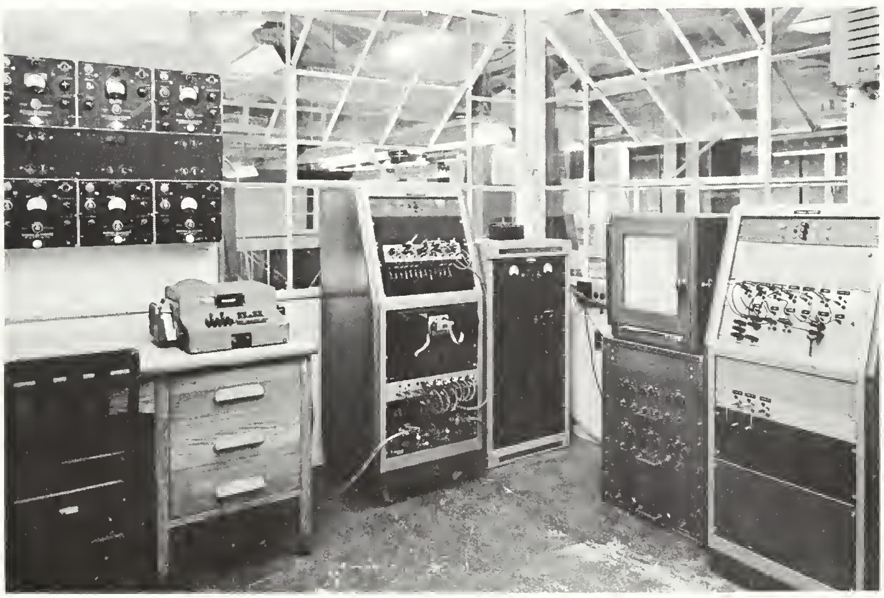
Heater Array

Fig. B-6



Overall View of Test Facility

Fig. B-7



Control Room

Fig. B-8

APPENDIX B REFERENCES

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